Preliminary Results and Future Goals for a Simultaneous Characterization of a Nested-channel Hall Thruster in Experiment and Simulation

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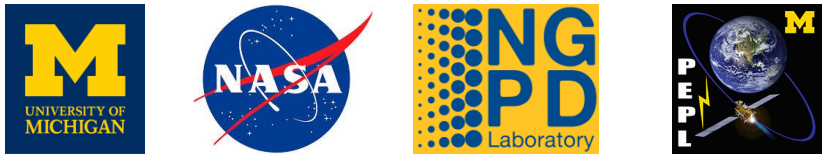
Funding provided through a NASA Space Technology Research Fellowship, grant numbers: NNX13AL51H and NNX14AL67H

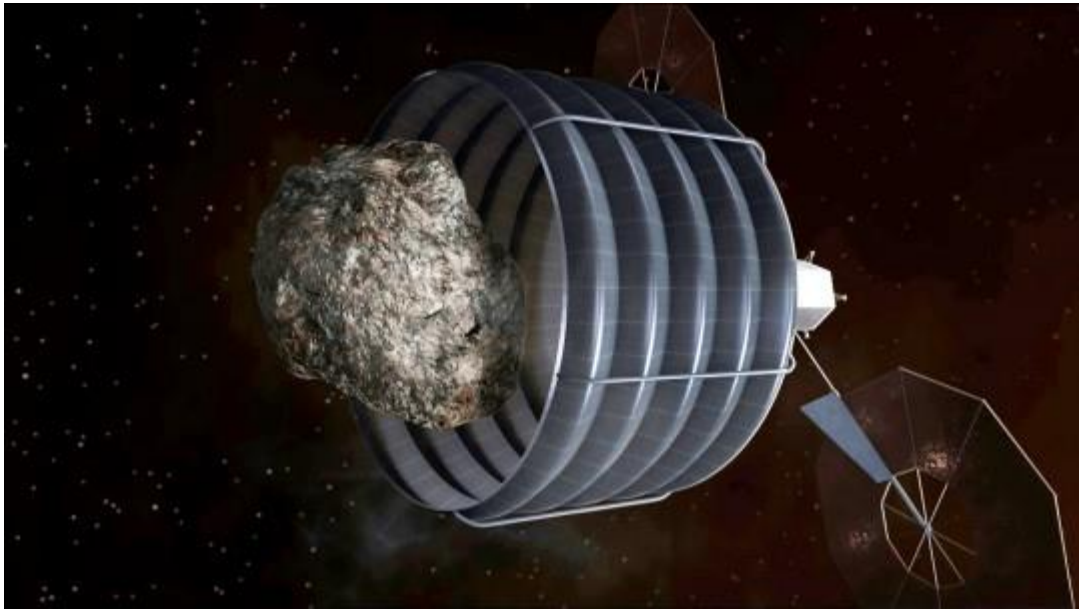


Outline

- NHT Motivation
- Development
- Experimental
  - Design Challenges
  - Preliminary results
  - Future work
- Modeling and Simulation
  - Setup
  - Preliminary results
  - Future work

Mission Pull for High Power EP

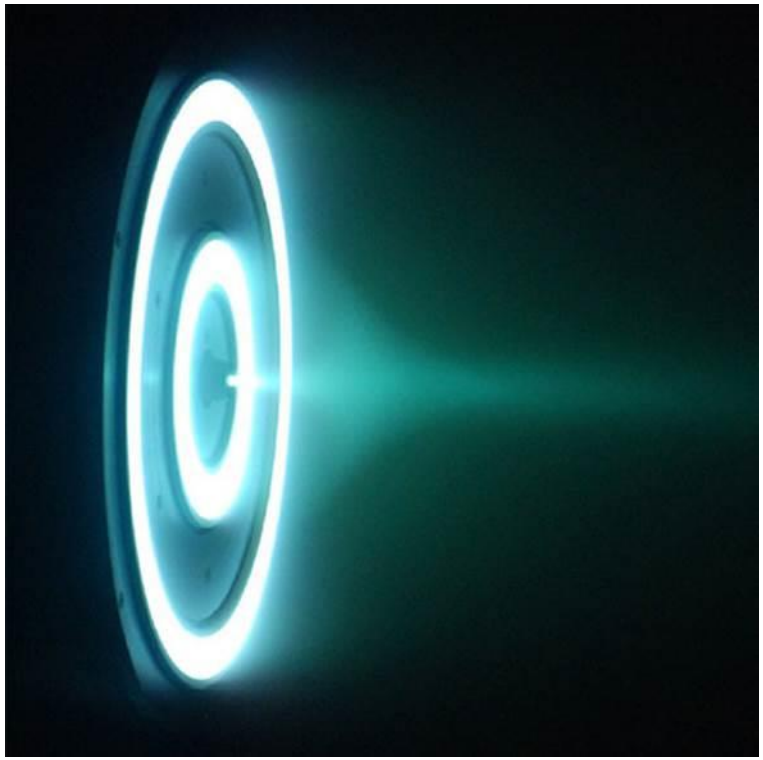
- Increased power required for:
  - Asteroid Redirect Mission (12.5 kW)
  - Space tugs (100's of kW)



Artist rendering of NASA's Asteroid Redirect Mission

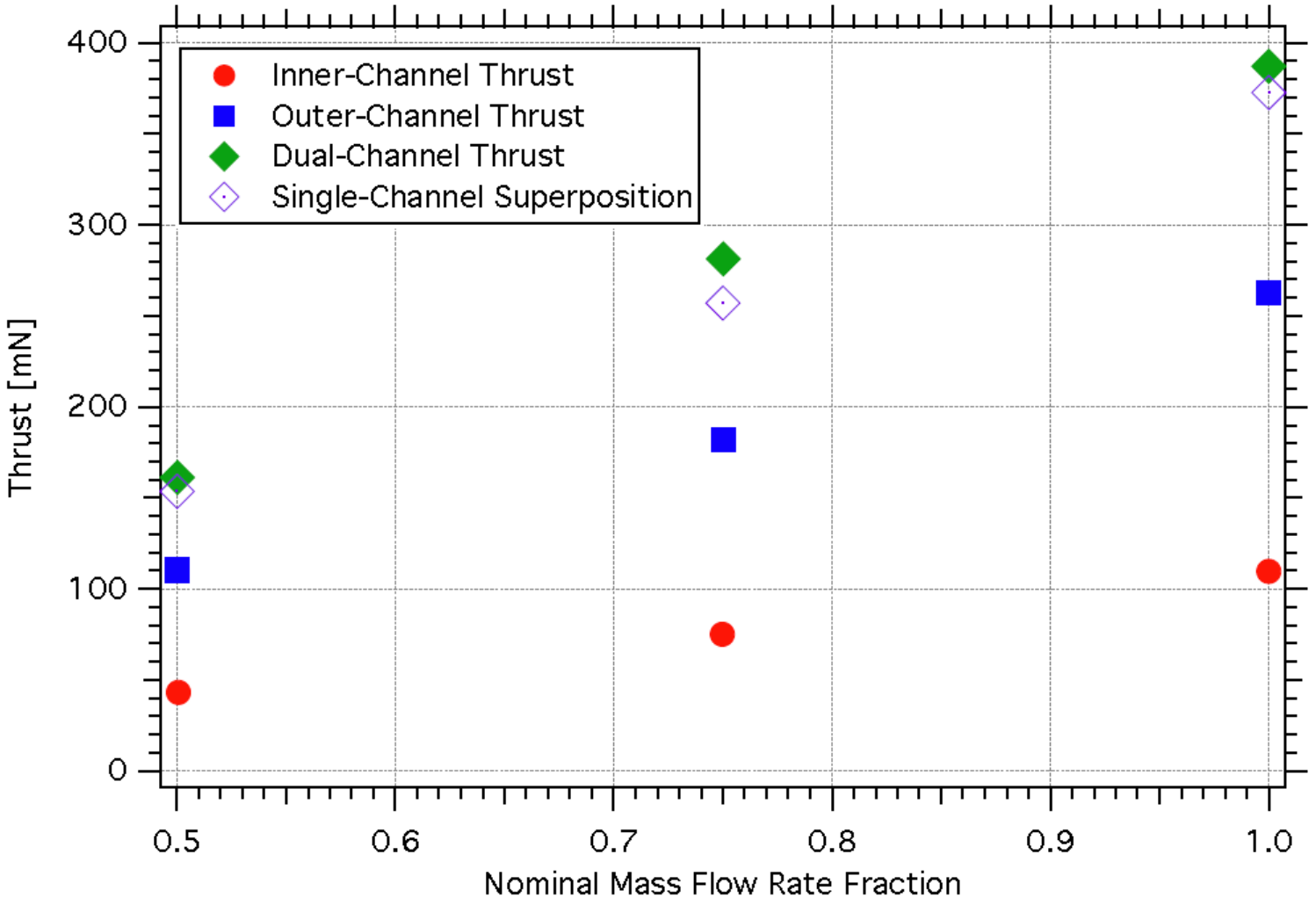
High Power with a Small Footprint

- Want to scale to large powers, but size is an issue
- Nested channels allow for higher power in a smaller footprint
- X2 is a proof of concept thruster developed at UM
- 2 channels, up to 10 kW discharge power
- Has been well characterized
- Currently used to validate simulation



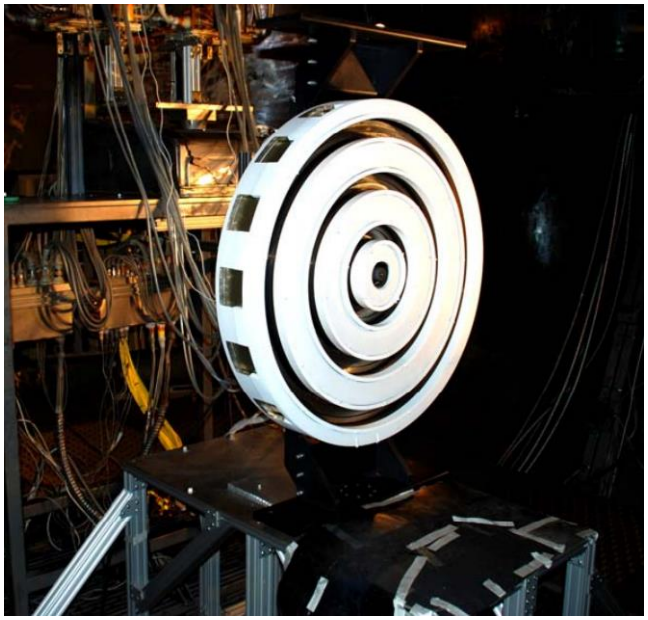
The proof-of-concept X2 nested-channel Hall thruster

Channel Interaction is Beneficial

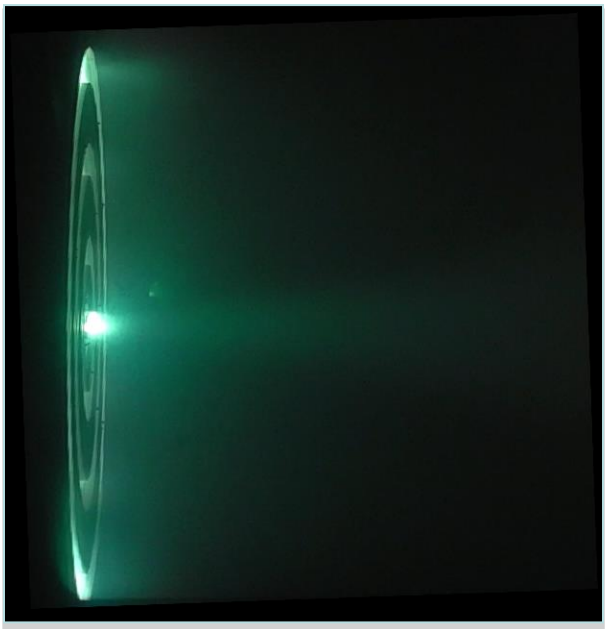


[1] Liang, R., "The Combination of Two Concentric Discharge Channels into a Nested Hall-Effect Thruster," Ph.D. Dissertation, Aerospace Engineering Dept., University of Michigan., Ann Arbor, MI, 2013.).

The X3: a 200-kW, Three-Channel NHT



Prior to first firing



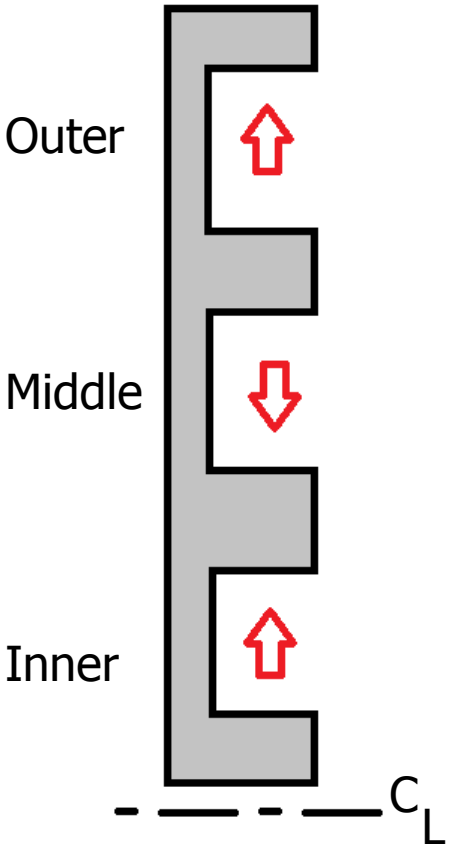
At 61 kW discharge power

- Builds upon X2 design
- ~ 1 m diameter
- Mass > 250 kg

- Designed: 2009-2011
- Built: 2012
- First firing: 2013

X3 Design

Magnetic Field

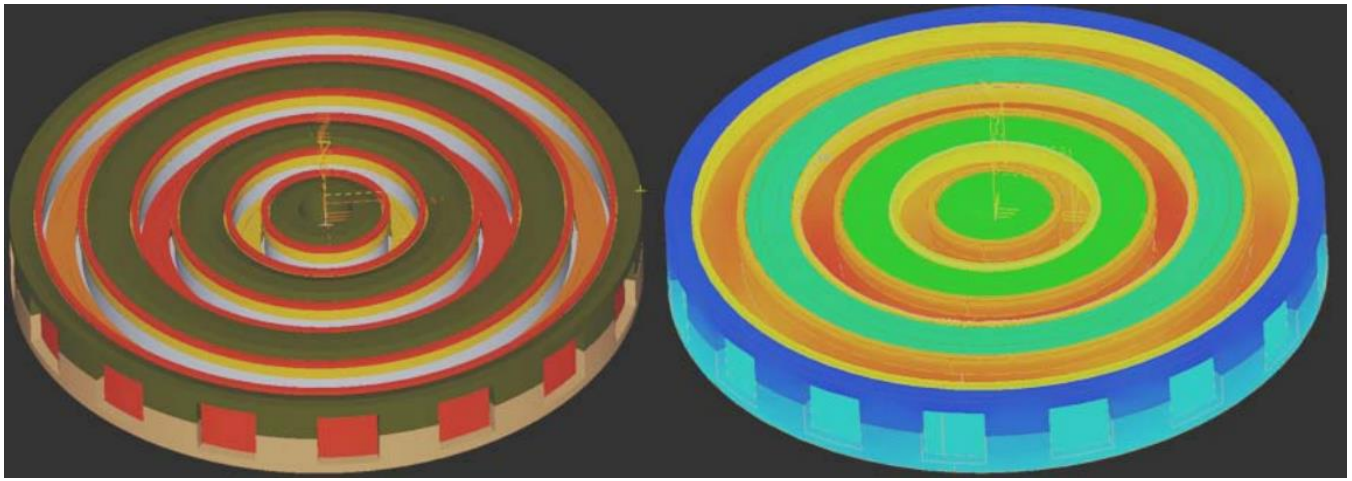


Cartoon illustrating channel magnetic field directions

- Each channel must be shaped correctly
- Additionally, channels must be independent
- Entire body of thruster is part of magnetic circuit
- The magnetic field for 3 channels required significant modeling

Concerns About Heat Dissipation

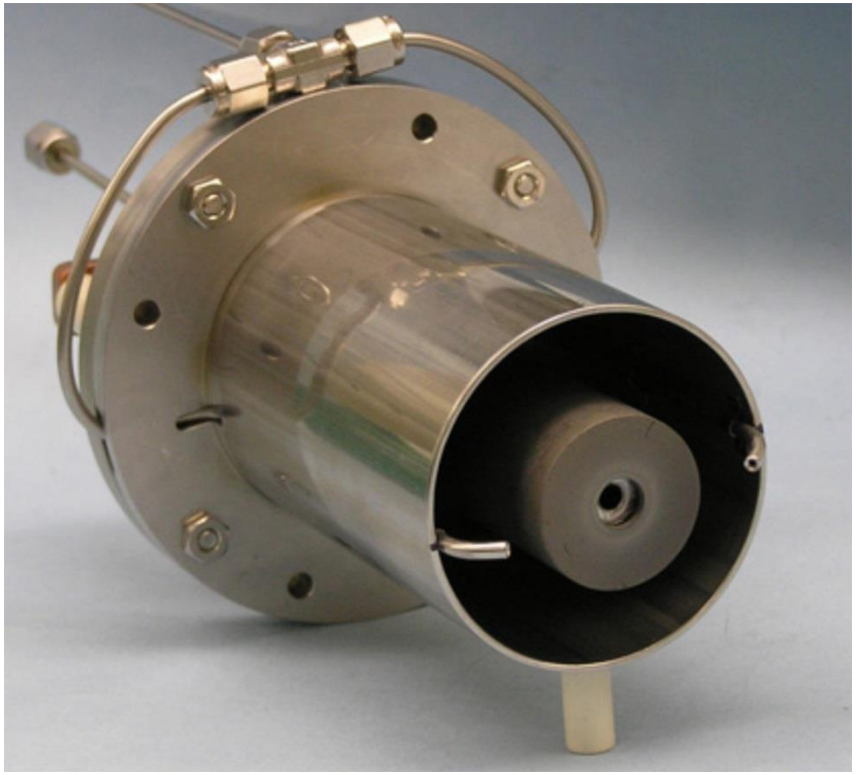
- Thermal modeling used in design process:
  - Material selection
  - Accounting for thermal expansion in tolerances
- Powers up to 200 kW



Images from thermal modeling tool

The X3 Cathode is Rated to 300 A

- Typical HET cathodes: 100 A
- X3 cathode: 300 A
- Specially designed by NASA JPL and NASA Glenn



The JPL-built cathode for the X3

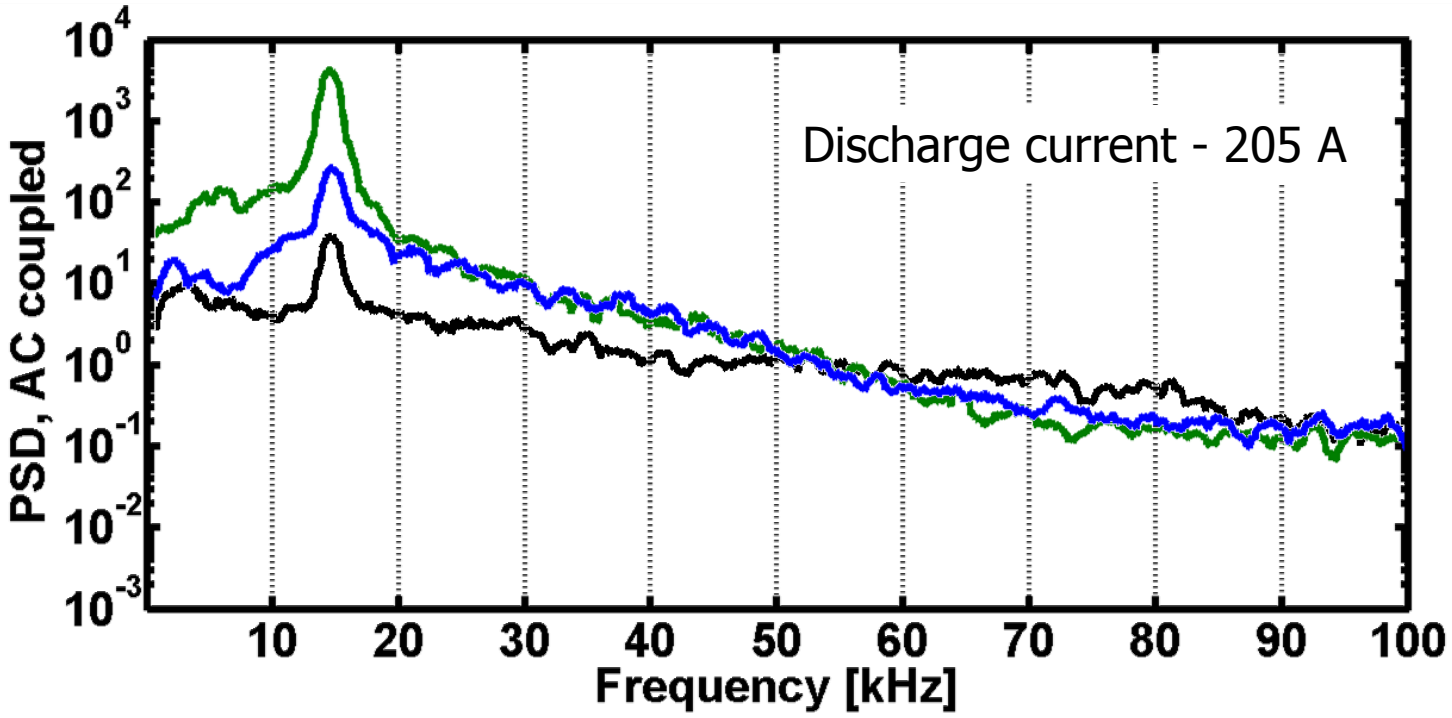
Preliminary Results

Initial Characterization

- The X3 has been run to 61 kW so far
- Testing to date has consisted of:
  - A 'burn in' period on krypton propellant
  - An 'initial characterization' on xenon propellant
- The initial characterization consisted of 2 'sets' of operating conditions
  - Each set contained the 7 operational modes of the thruster
  - Sets at constant current density: 37% and 73% nominal

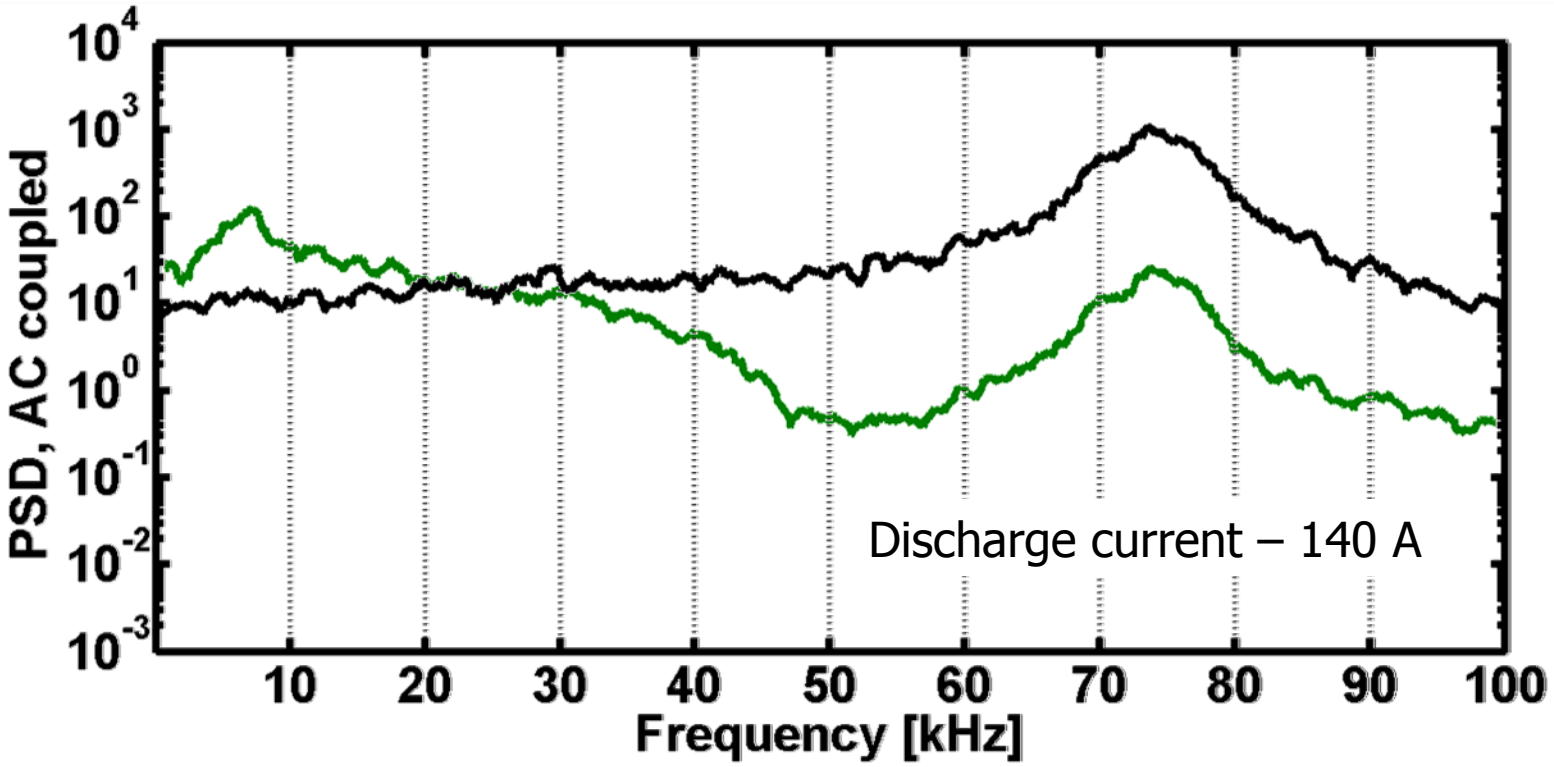
Breathing Mode

- High-speed current probes yield Power Spectral Densities (PSDs)
- Breathing modes converge (to varying degrees)
- Strongest in 3-channel mode



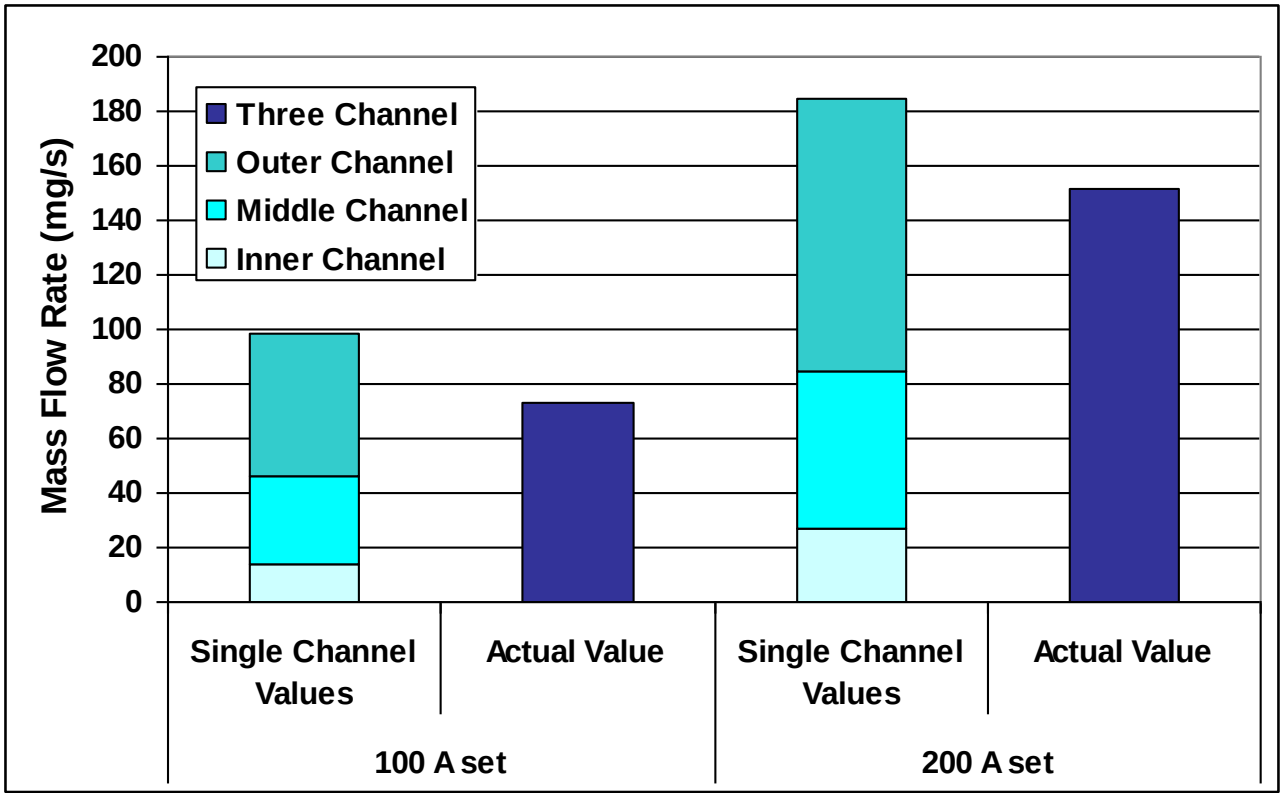
Channel Coupling

- An anomalous "hump" appears at 73 kHz in the inner channel PSD
- The same hump appears in the outer channel PSD



Unexpected Propellant Savings

- Propellant usage in multi-channel modes is less than the sum of the channels running individually



Three-channel mode propellant flow rates as compared to summed single-channel mode values

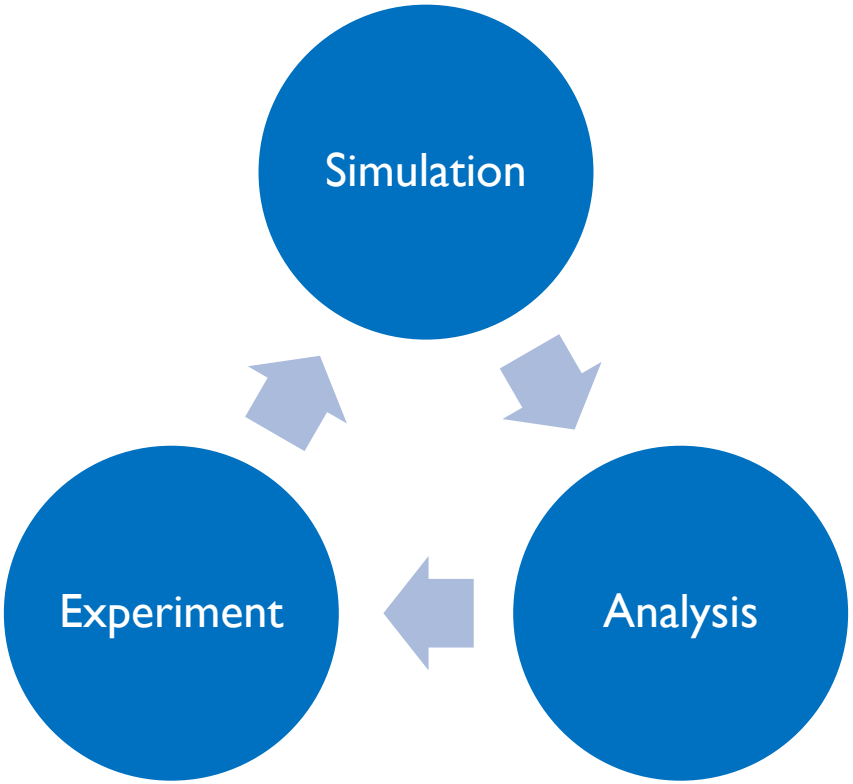
Future Experimental Work

- Run thruster through entire operational envelope, up to 200 kW
  - A larger vacuum chamber is necessary: VF5 at NASA Glenn, perhaps B2 at Plum Brook
  - Will mimic the 'initial characterization' done at PEPL
- Full thruster characterization
  - Measure thrust
  - Use suite of plasma probes to fully analyze plume characteristics in the near- and far-field
- Collaborate with a modeler in real time throughout

Modeling and Simulation

Motivation for Simulations and Modeling of the Channels

- Full characterization of the thruster channels
- Hard to measure quantities inside channel
- Future input for a plume simulation
- Investigation of channel interaction
- Design feedback



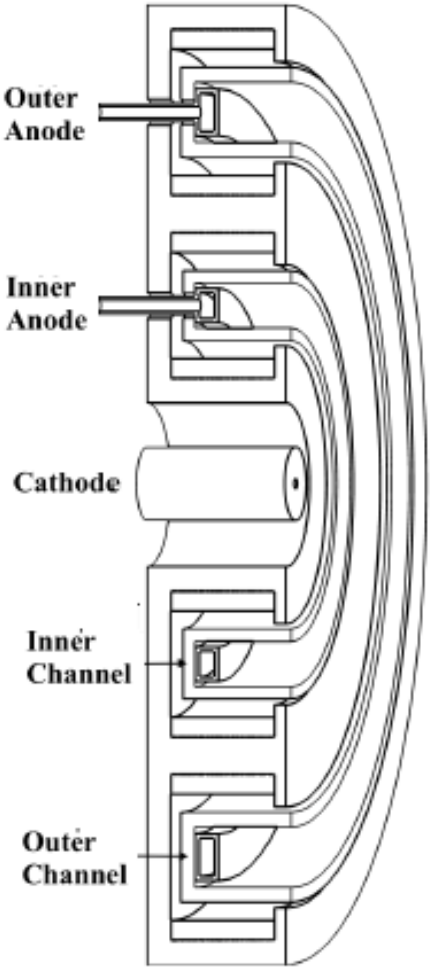
Simulation Strategy

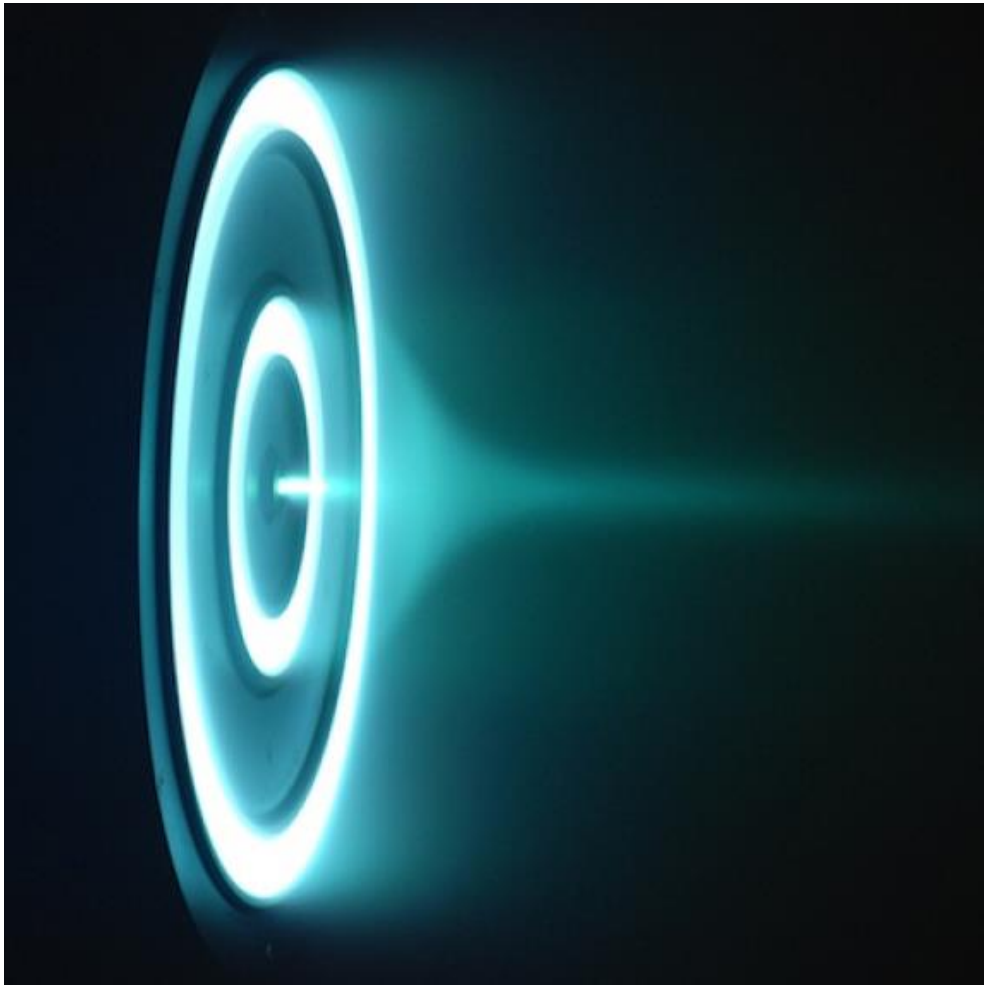
- Using 2D axisymmetric hybrid code HPHall [2]
- First the X2 is used for validation
  1. Inner channel
  2. Outer channel
  3. Dual channel
- Then the X3 will be investigated
  1. Single channel
  2. Combinations of dual channel operation
  3. Triple channel operation

[2] Fife, J.M., “Hybrid-PIC Modeling and Electrostatic Probe Survey of Hall Thrusters," Ph.D. Dissertation, Dept. of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, MA, 1998.).

X2 Inner Channel Simulation Setup

X2





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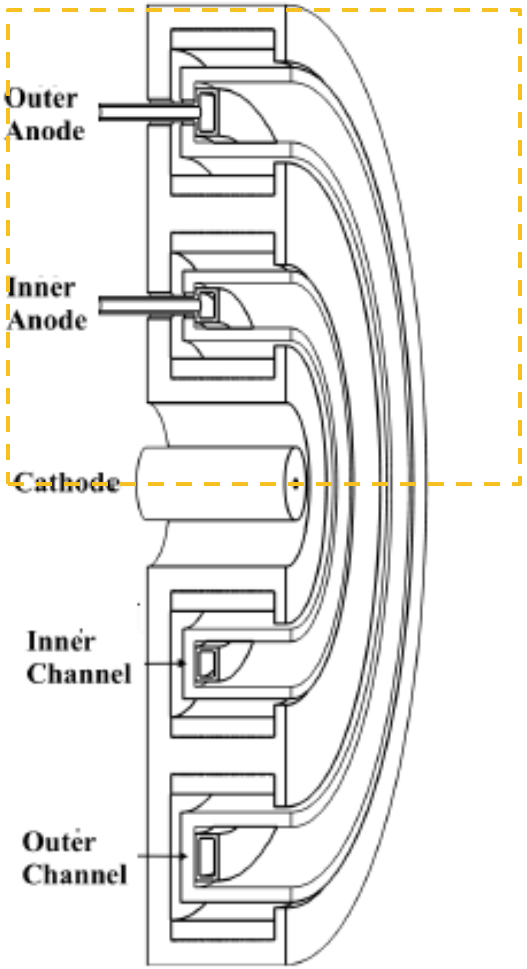
Axisymmetric – 2D



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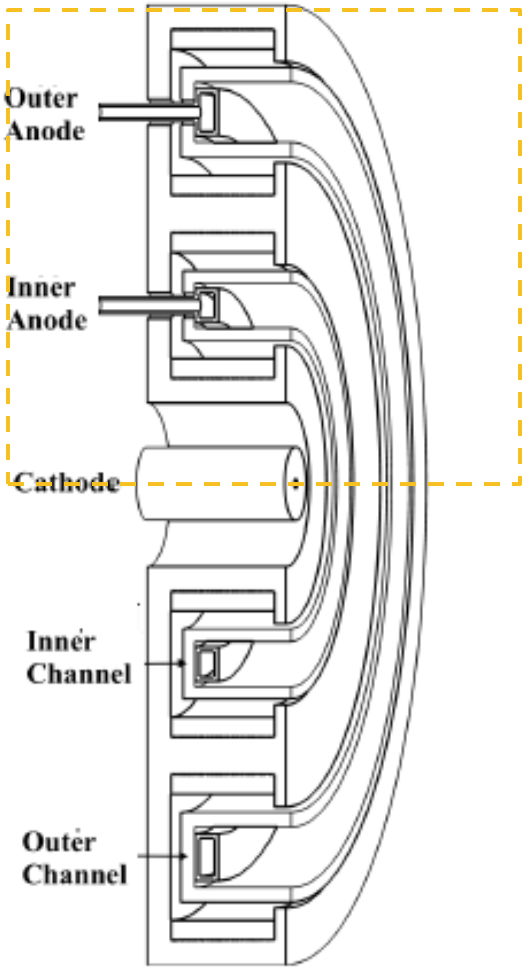

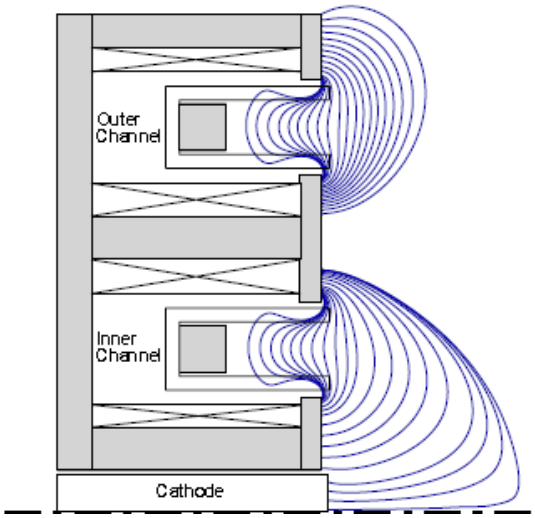

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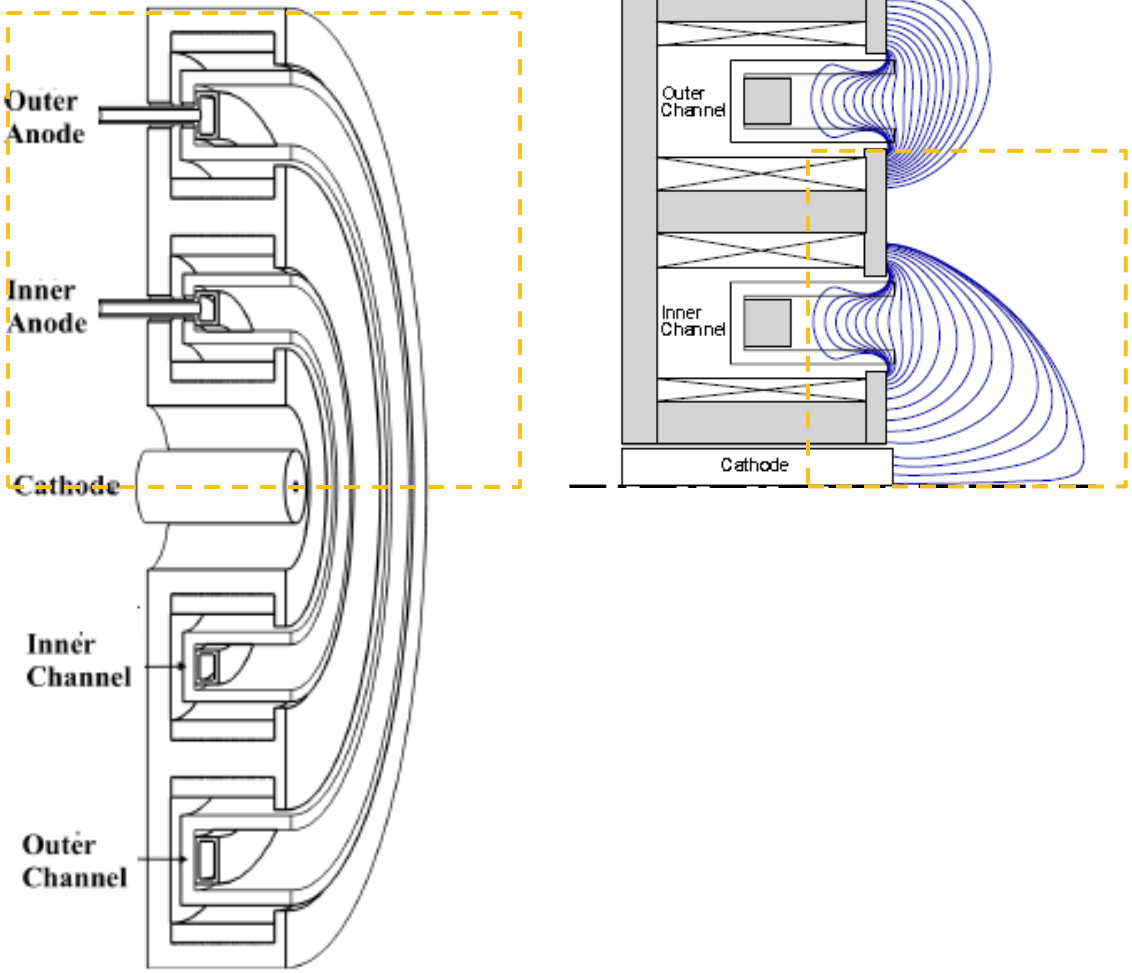
Axisymmetric – 2D



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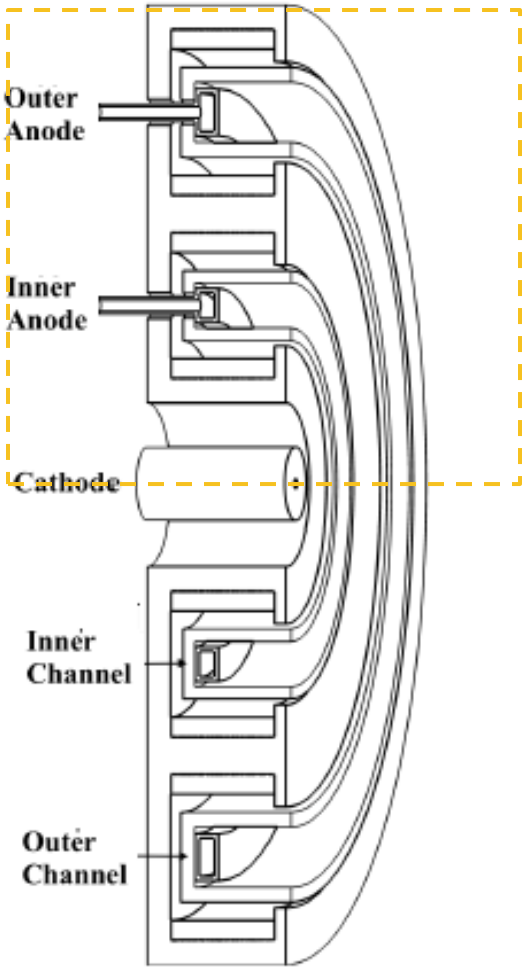
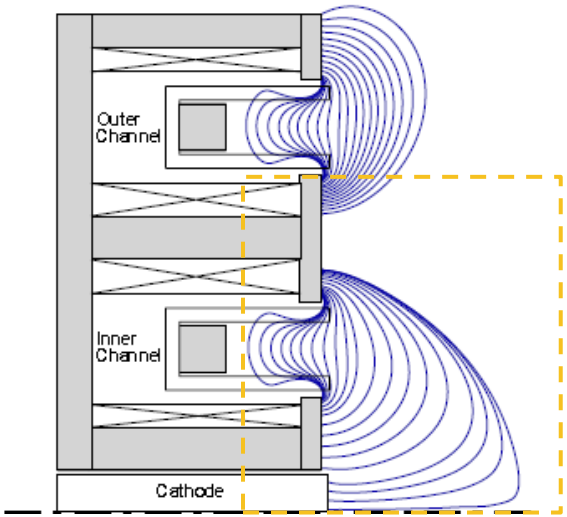
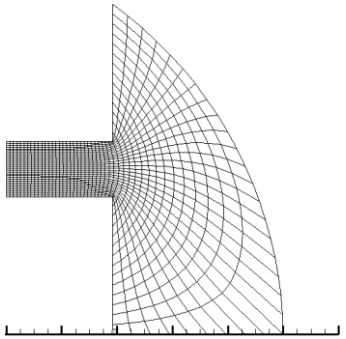
Inner Channel







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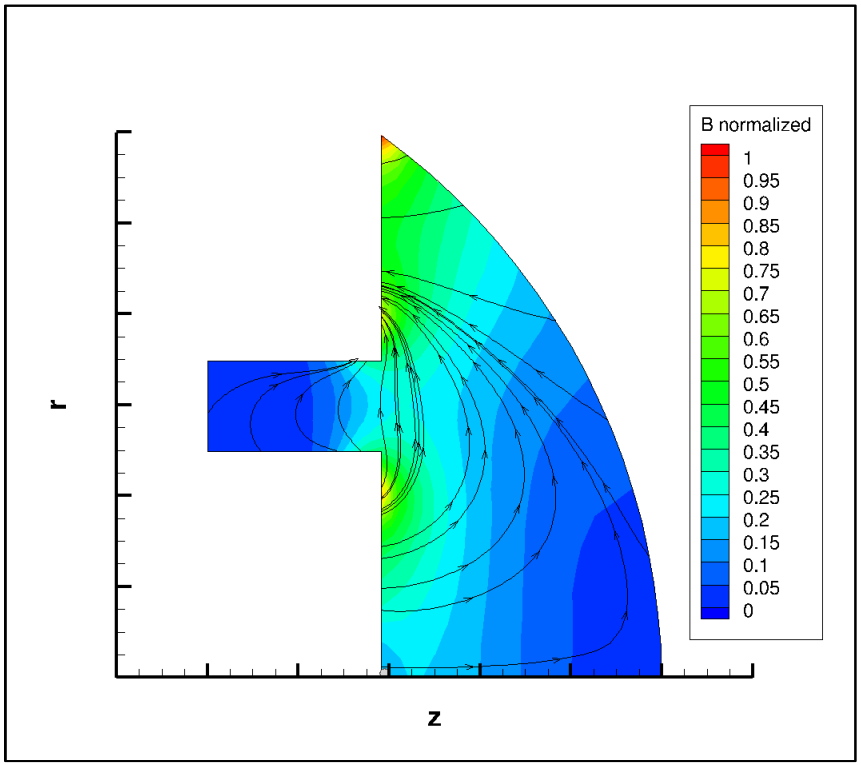
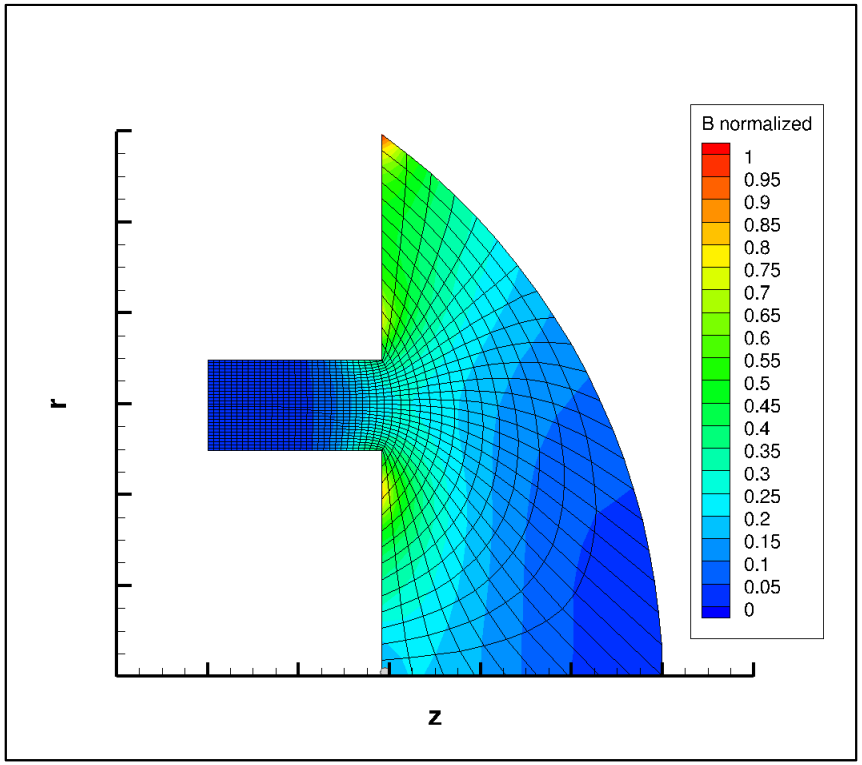
Magnetic Field and Mesh



B field lines



Mesh

Simulation Parameters

Propellant gas	Xe
Total number of neutrals (macroparticles)	133,000
Total number of ions (macroparticles)	613,000
Total simulation time	4 [ms]
Simulation timestep	$5 * 10^{-8}$ [s]
Propellant flow rate	7 [mg/s]
Discharge voltage	200 [V]
Wall temperature	812 [K]
Computation time	22 [hrs]

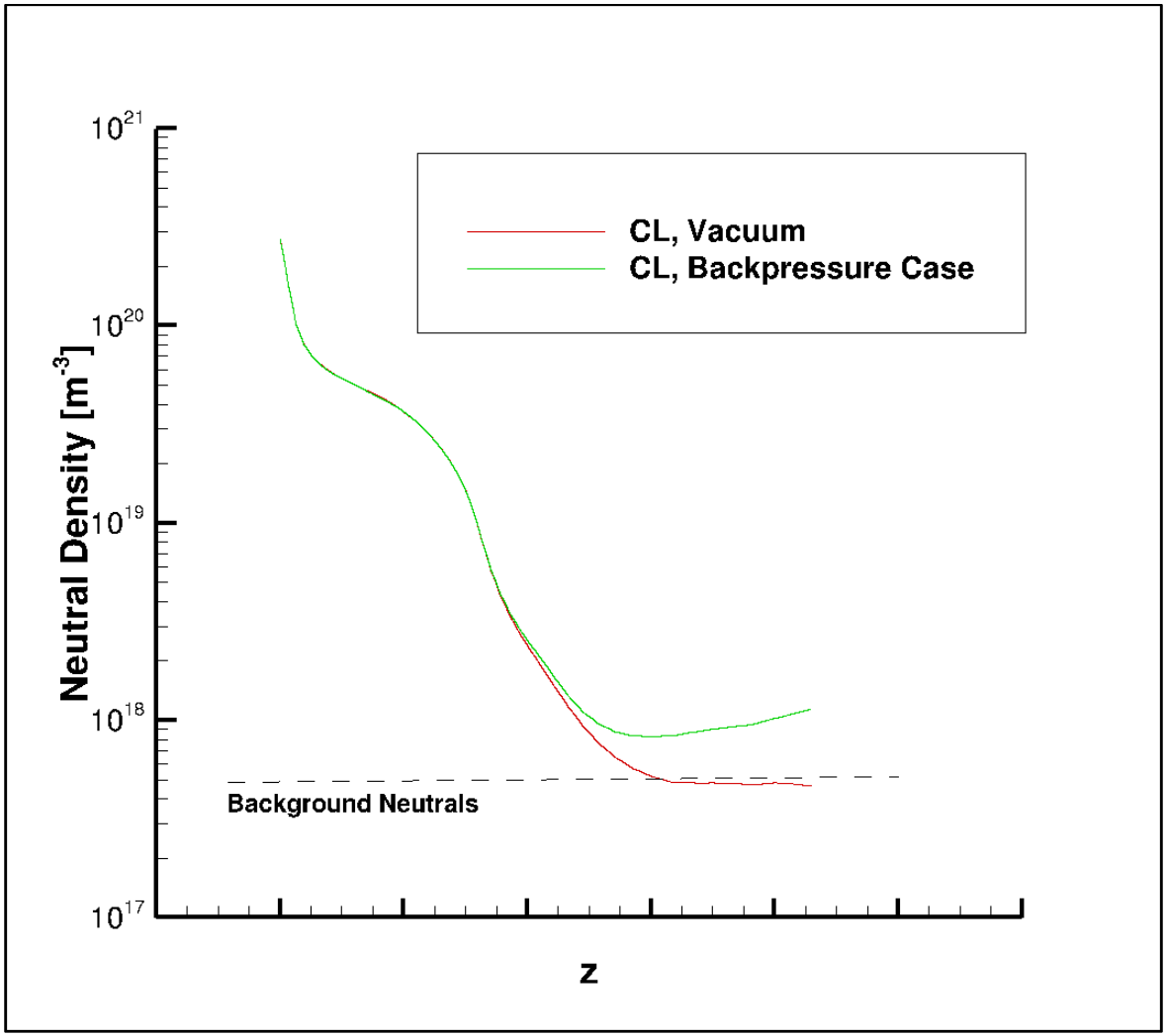
Simulation Results

Results

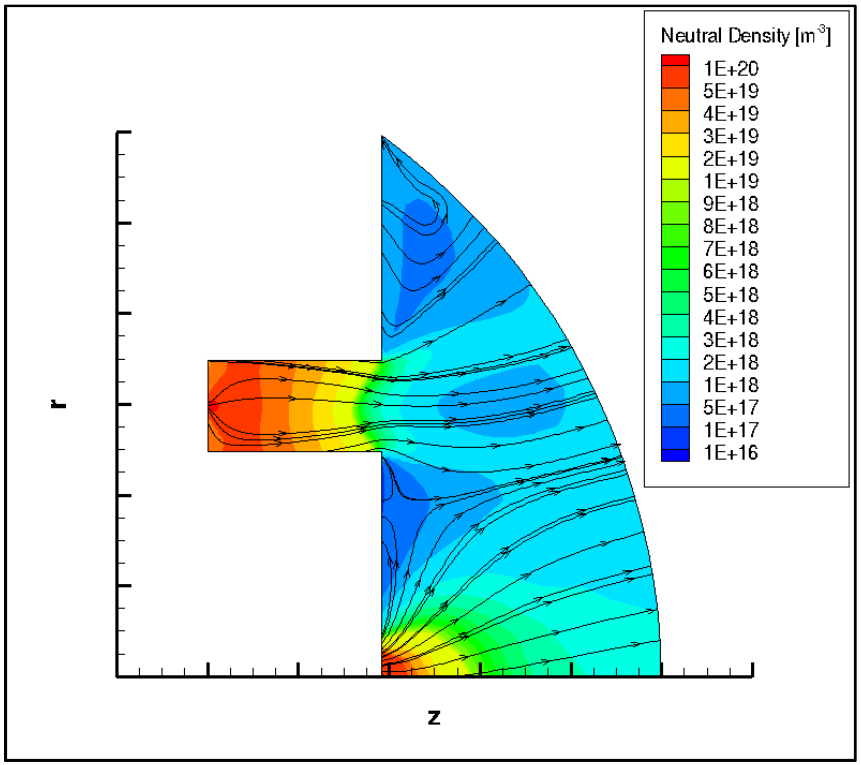
- Successfully ran 2 simulations for the inner channel:
  - in vacuum
  - with the reported facility background pressure ($1.5 * 10^{-5}$ Torr)
- The thrust value difference was within statistical error

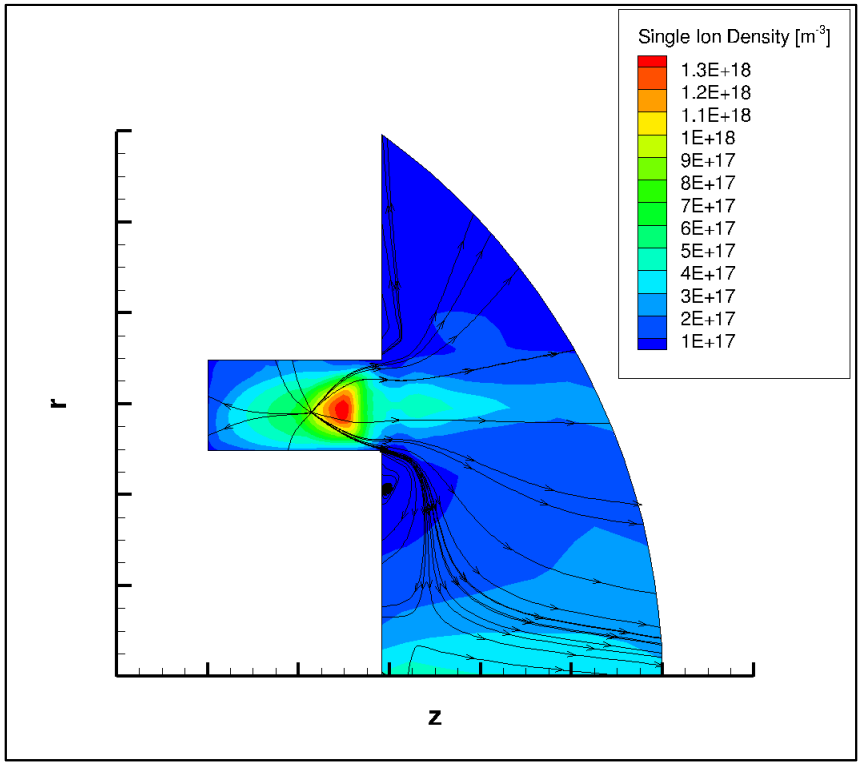
Thrust Values (mN)		
Measured	Simulation in vacuum	Simulation with LVTF backpressure
92.0 ± 3.00	88.5 ± 0.342	88.4 ± 0.273

Neutral Number Density Comparison Along CL

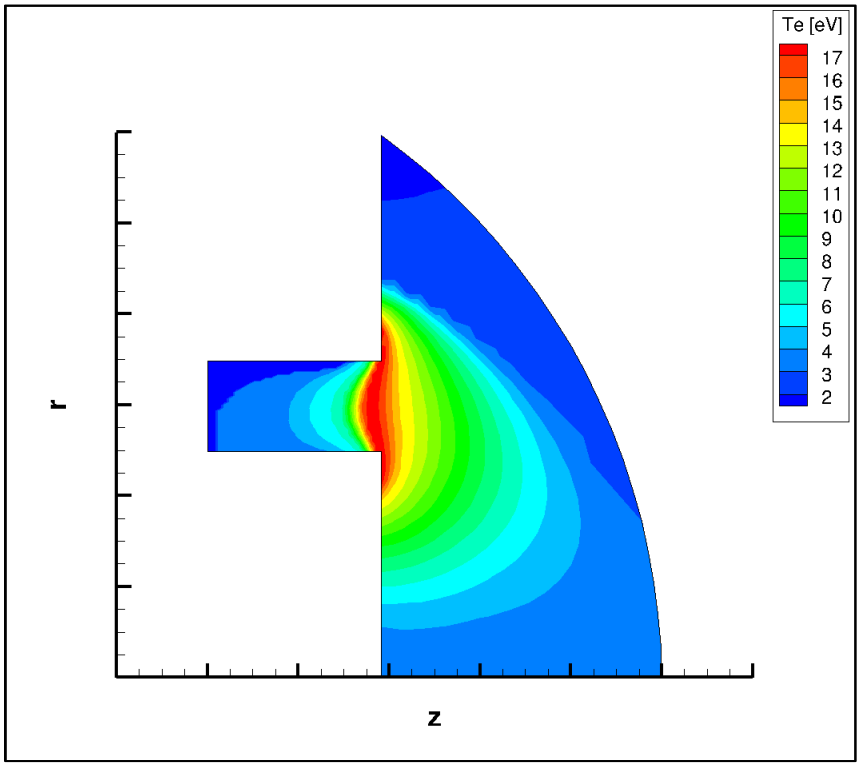


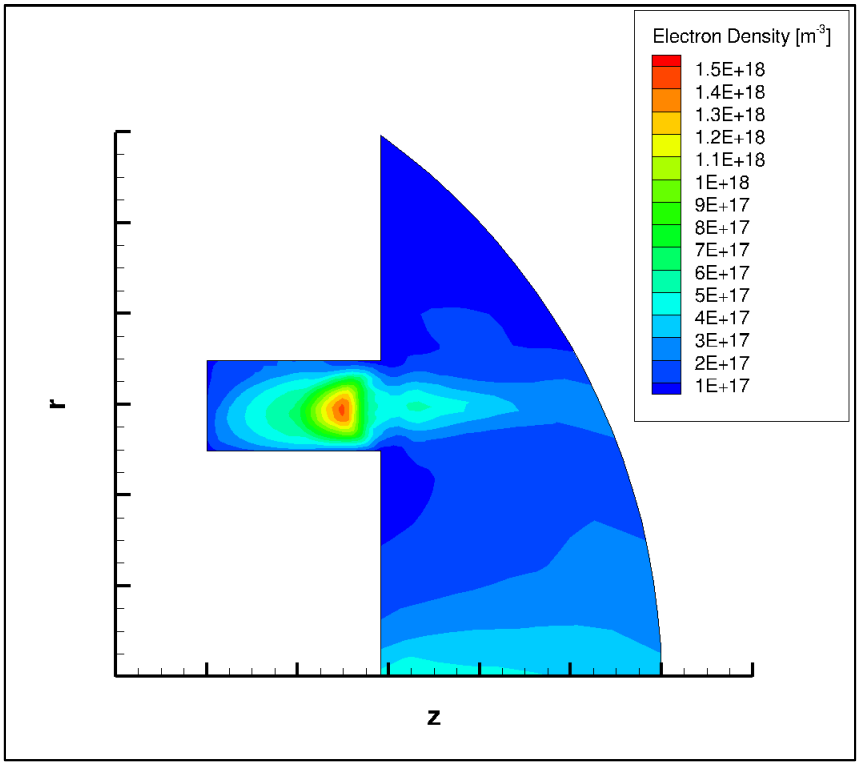
Xe and Xe+ Number Densities





Electron Temperature and Number Density





Preliminary Conclusions

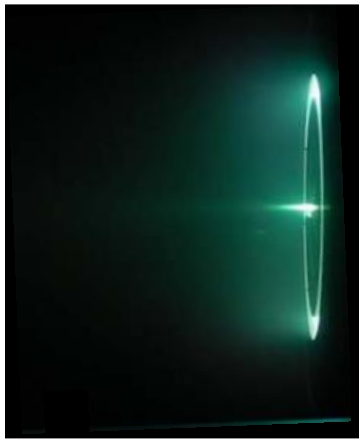
- Facility backpressure does not influence the inner channel
- Thrust values are in good agreement with measurement
- Do not expect triply charged Xe ions

Future Modelling Work

- Near term:
  - Compare measured centerline values of electron temperature and plasma potential with simulation results
  - Measure B field and compare to MagNet results (verification)
  - Obtain B field from MagNet for other thruster operating conditions
  - Prepare outer channel simulation
- Medium term:
  - Update code
    - Electron model
    - Mesh reading routine
  - Prepare dual channel simulation
- Long term:
  - Move on to X3 simulations

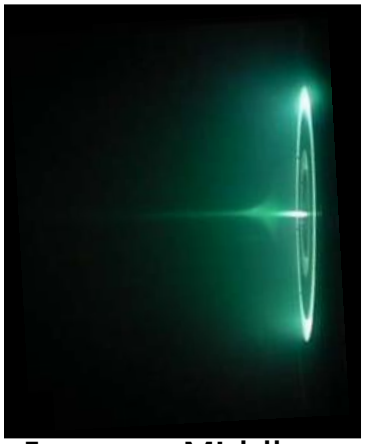
Questions?

Inner

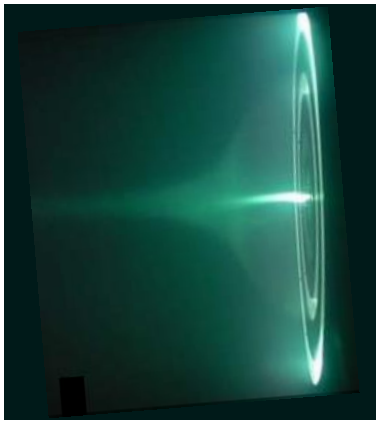


Middle

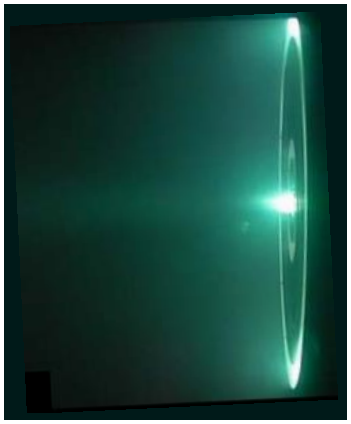
Outer



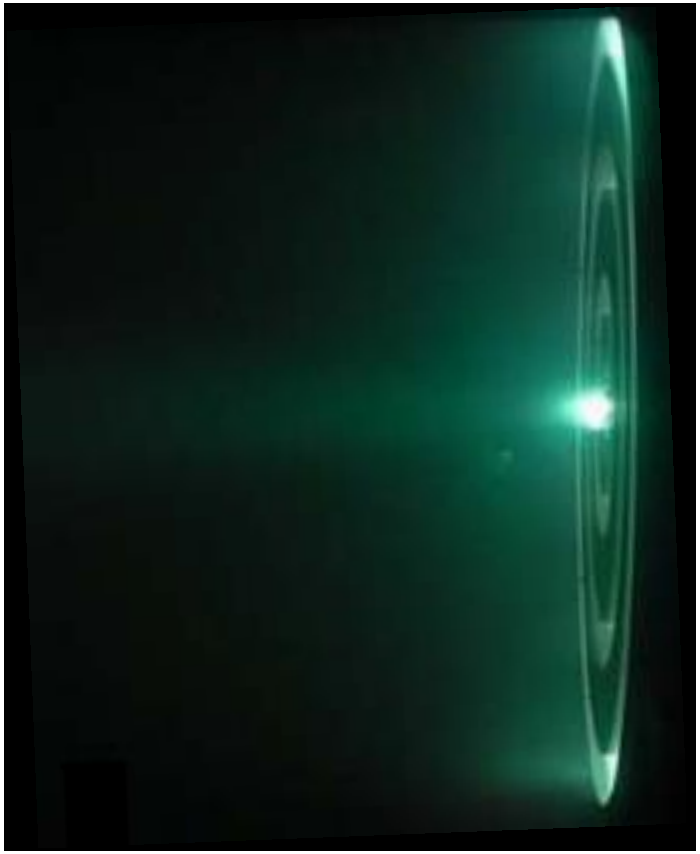
Inner + Middle



Middle + Outer



Inner + Outer



Inner + Middle + Outer: 61 kW total discharge power

Backup Slides

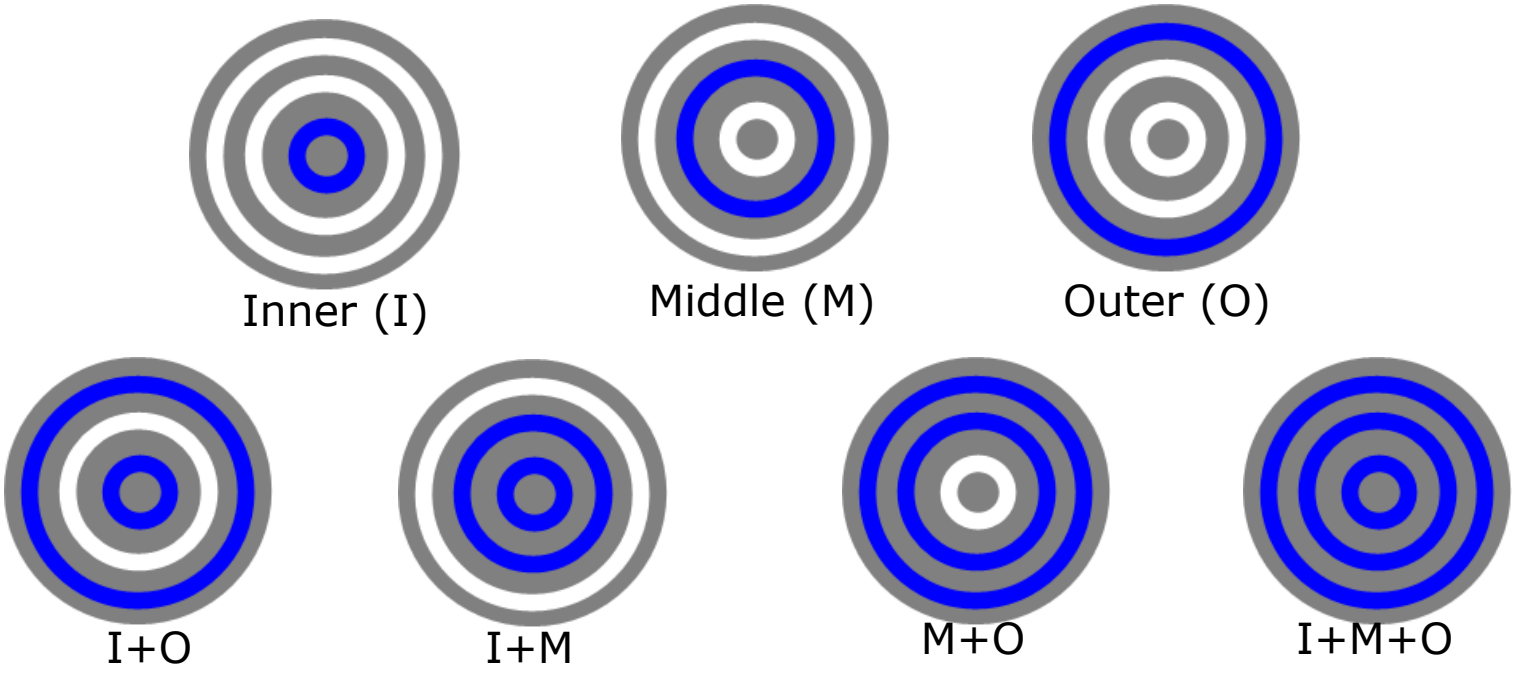
Comparison to Chemical Propulsion

Parameter	One Space Shuttle Solid Rocket Booster	Typical Hall-Effect Thruster (HET)
Application	Surface to LEO	In-space
Thrust	2,270,000 N	0.05-0.1 N
Specific Impulse	269 s	2000-3000 s
Power	4.9 GW	6 kW
Burn Time	127 s	5 years
Propellant Mass	500,000 kg	3,060 kg
Propellant Type	Aluminum Perchlorate	Xenon
Total Energy	620 GJ	620 GJ

Vacuum Facility

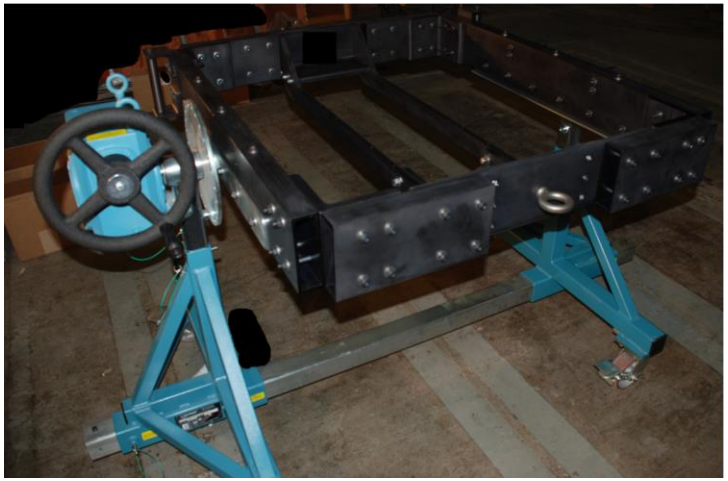
- Testing has occurred in the Large Vacuum Test Facility at PEPL
  - A 9 m long, 6 m diameter stainless-steel-clad vacuum chamber
  - 4 mechanical pumps, 2 blowers to rough vacuum; 7 cryopumps to full base pressure
  - Base pressure of 1×10^{-7} Torr (1×10^{-10} atm)

The X3's channels can be run separately or together in any combination

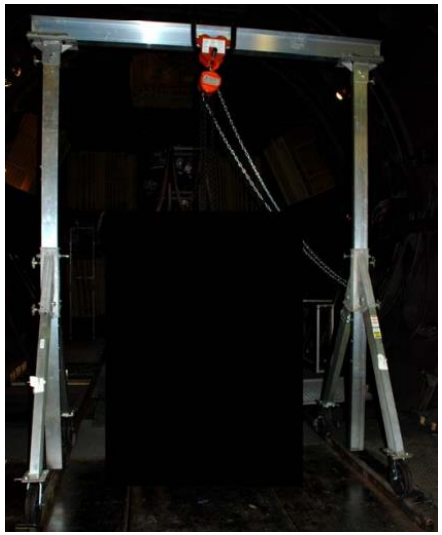


The X3 non-trivial to handle it safely in the lab

- Typical laboratory HETs can be carried by one or two people
- The X3 needs:
  - a cart for storage
  - a crane for installation in the vacuum chamber

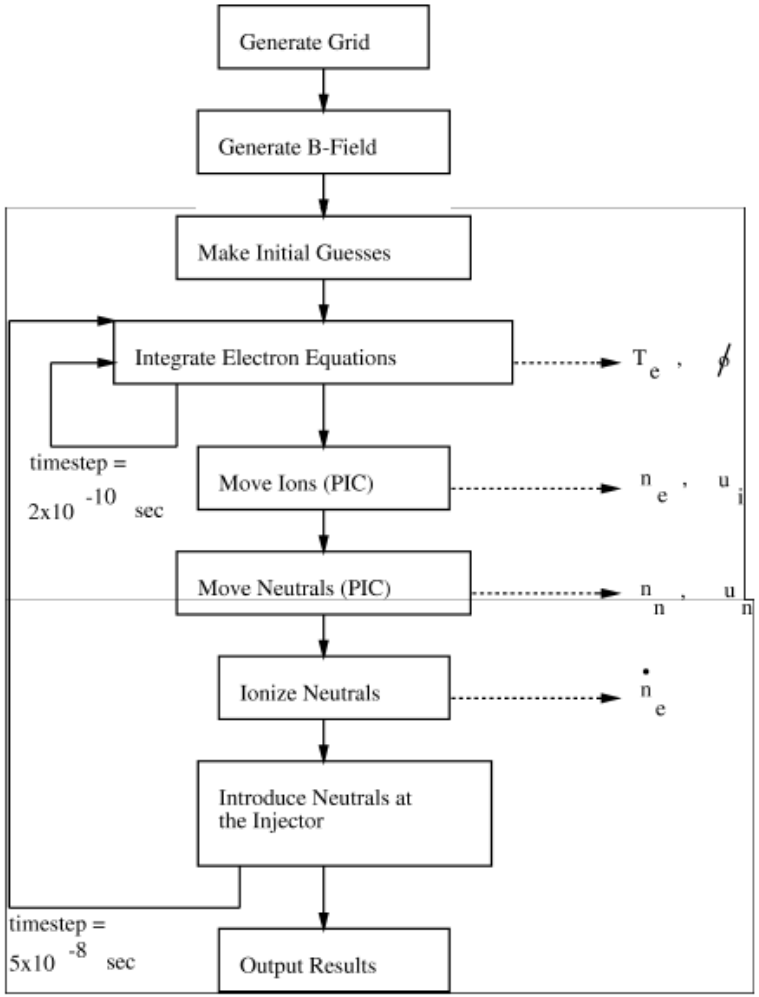


Holding fixture used as the assembly rig for the X3



Gantry crane

Code Execution Sequence



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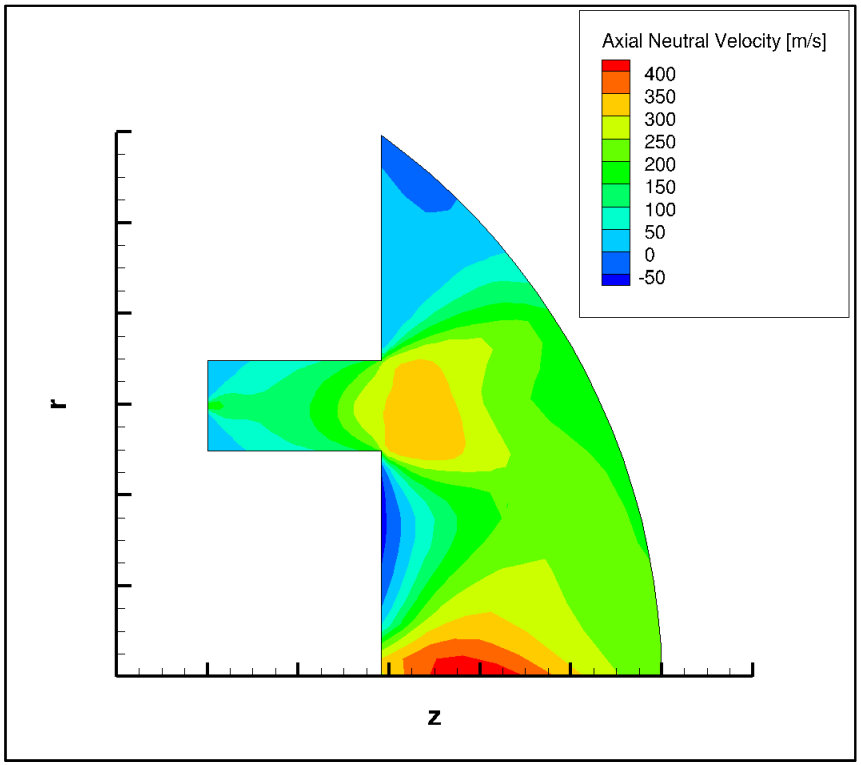
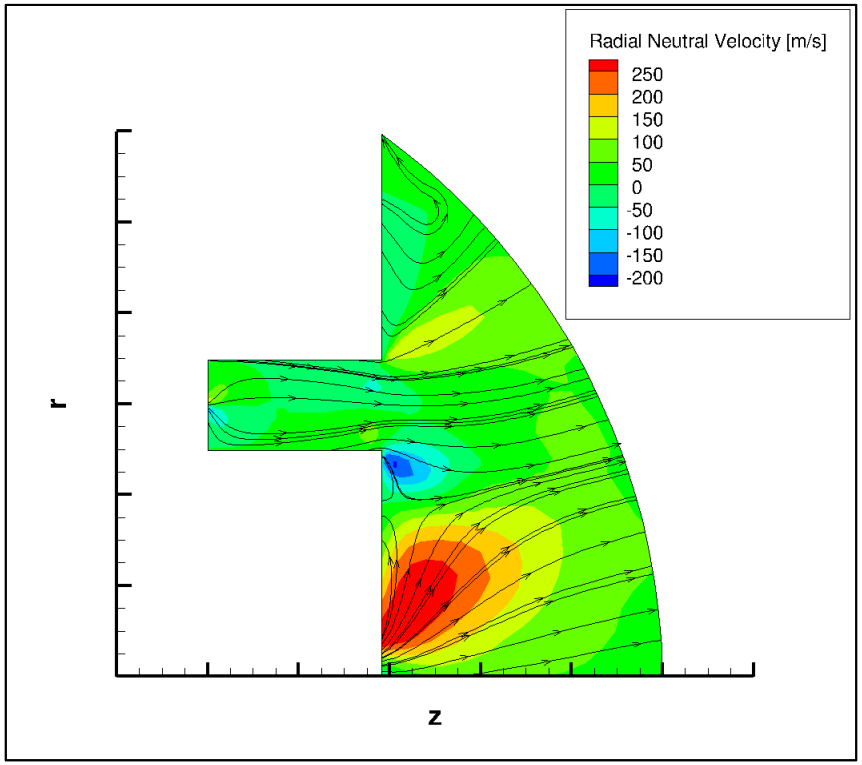
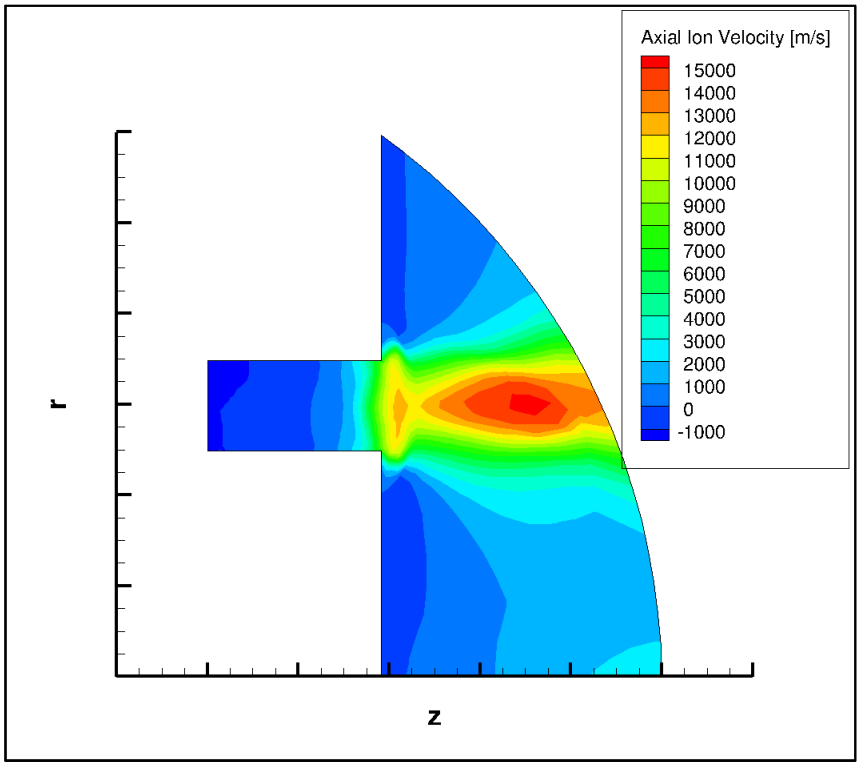
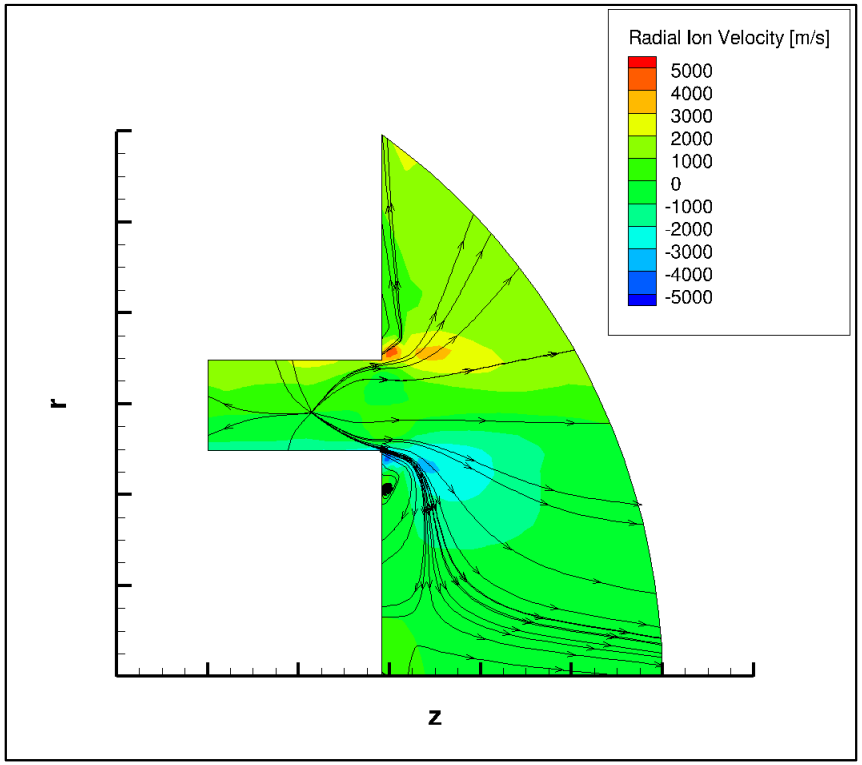
Xe Velocities



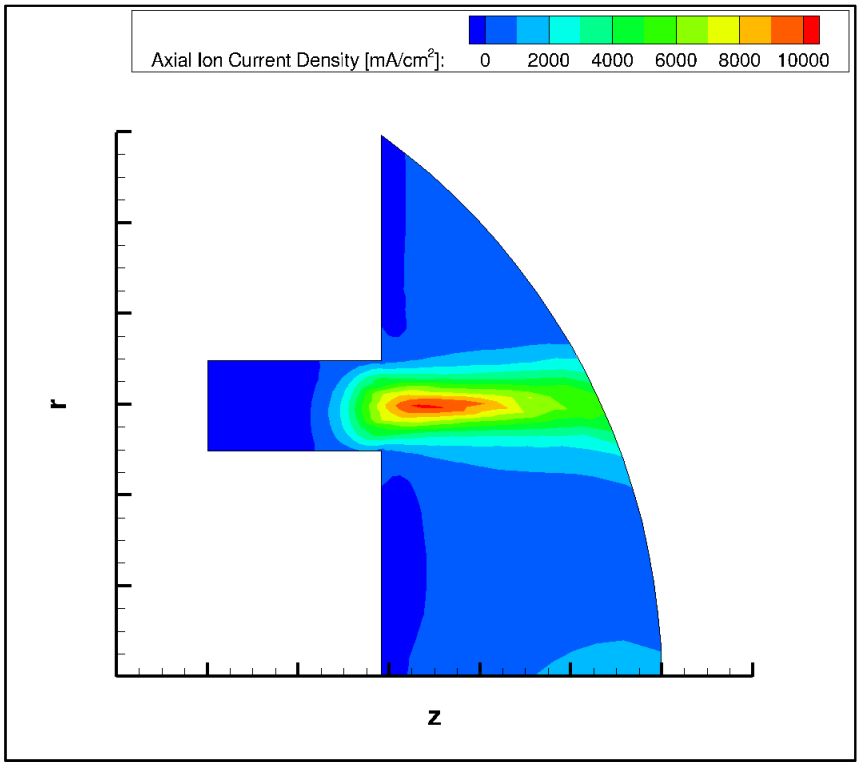


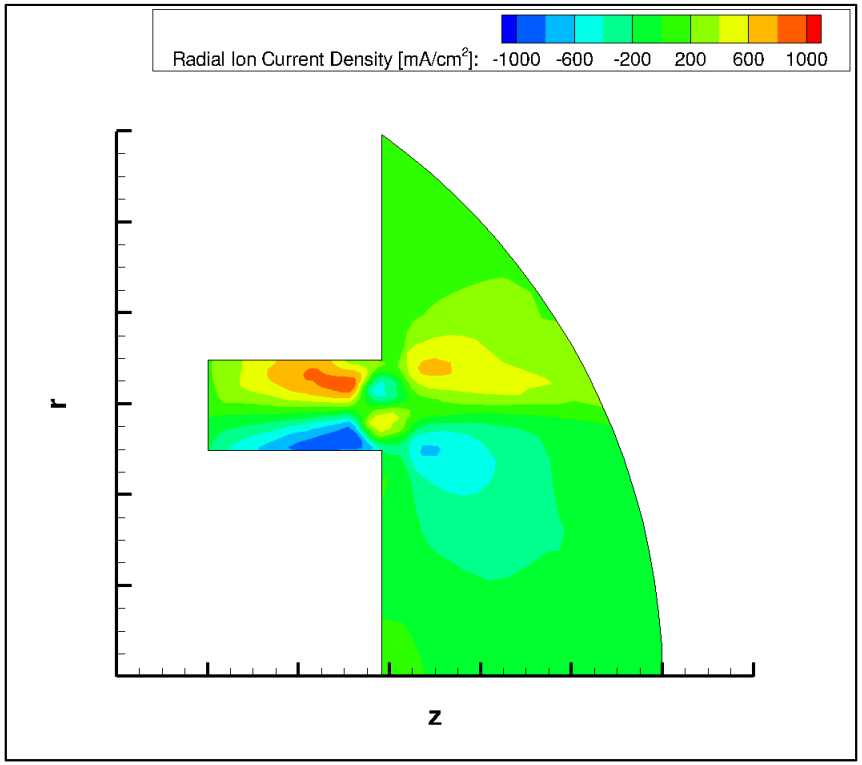
Xe+ Velocities





Ion Current Density





Plasma Potential